National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

A Geostationary Microwave Sounder

Design and Applications

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AIRS Science Team Meeting

Pasadena, CA; March 27-30, 2007

Summary

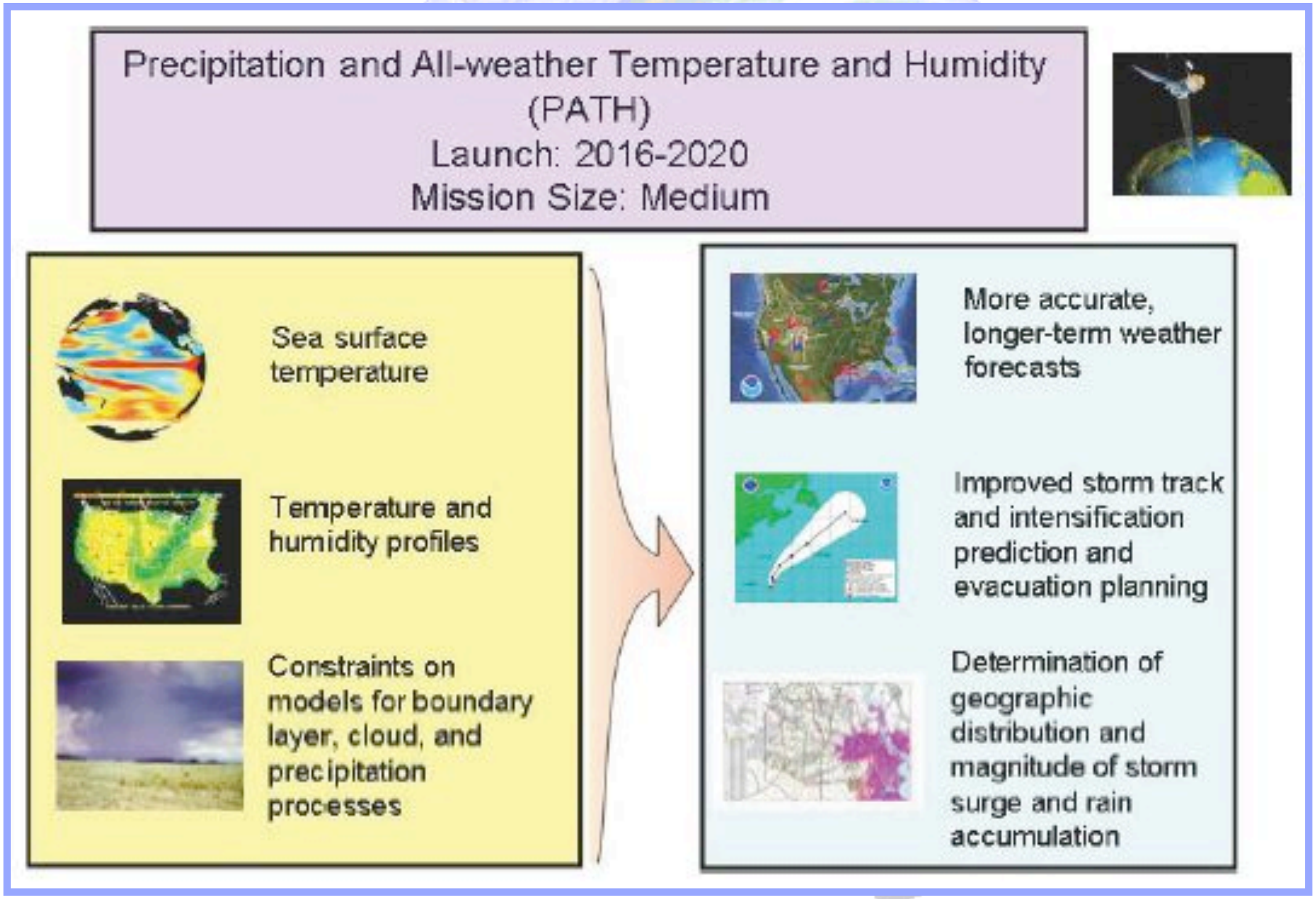
- **GeoSTAR is a microwave sounder intended for GEO**
  - Ground-based proof-of-concept prototype has been developed
    - ***Excellent performance => Breakthrough development!***
  - Space-based version can be developed in time for GOES-R/S (2014-16)
- **Functionally equivalent to AMSU**
  - Tropospheric T-sounding @ 50 GHz with ≤ 50 km resolution
    - *Stand-alone all-weather temperature soundings*
    - Cloud clearing of IR sounder
  - Tropospheric q-sounding @ 183 GHz with ≤ 25 km resolution
    - *Stand-alone all-weather water vapor/liquid water soundings*
    - *Rain mapping*
    - *Tropospheric wind profiles* (Only feasible from GEO)
- **Using *Aperture Synthesis***
  - Also called Synthetic Thinned Array Radiometer (STAR)

Why?

- **GEO sounders achieve high temporal resolution**
  - LEO: Global coverage, but poor temporal resolution; high spatial res. is easy
  - GEO: High temporal resolution and coverage, but only hemispheric non-polar coverage; high spatial res. is difficult
  - Requires equivalent measurement capabilities as now in LEO: IR & MW
- **MW sounders measure quantities IR sounders can't**
  - Meteorologically "interesting" scenes
    - Full cloud cover; Severe storms & hurricanes
  - Cloud liquid water distribution
  - Precipitation & convection
- **MW sounders complement IR sounders**
  - Complement primary IR sounder (HES) with matching MW sounder
    - Until now not feasible due to very large aperture required (~ 4-6 m dia. in GEO)
  - Microwave provides cloud/"cloud-clearing" information
    - Requires T-sounding through clouds - to surface under all atmospheric conditions
- **A MW sounder is one of the most desired GEO payloads**
  - High on the list of unmet capabilities

NRC Decadal Survey

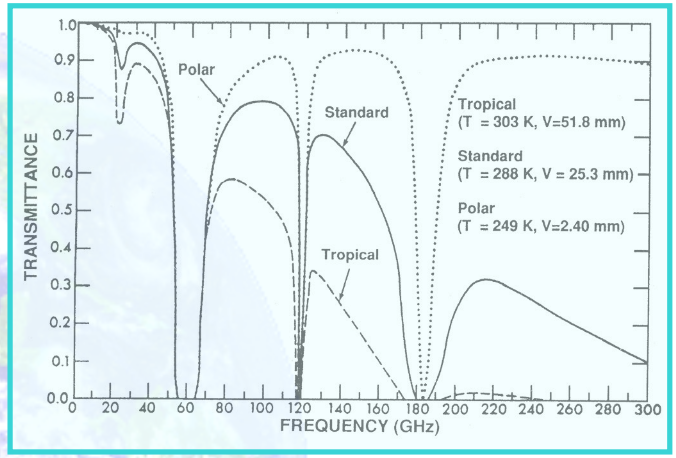
NRC Decadal Survey recommends "PATH" (= GeoSTAR)!



Why No MW/GEO Sounder Already?

- **Difficult to build large enough aperture**
  - AMSU-equivalence requires 6 meter parabolic dish: Difficult to stow and deploy
  - High surface fidelity required for adequate beam efficiency: Beam efficiency of 95%+ required for sounding
  - Mesh or film technology not available at sounding frequencies: Must use solid dish
    - Means large volume, mass, moment of inertia
- **Difficult to achieve adequate spatial coverage**
  - Dish antenna must be mechanically scanned: Difficult to scan very large dish
  - Scanning subreflector is problematic: Beam quality/efficiency degrades with scan angle
    - Therefore, scan range is limited
- **Difficult to overcome system limitations**
  - Mechanical scanning causes platform disturbances: Cannot coexist with super-high resolution imagers
  - Large platform resources required: Mass, power, volume, platform control
  - High risk at system level
  - Difficult to expand to meet future growing needs

Notional Measurement Requirements

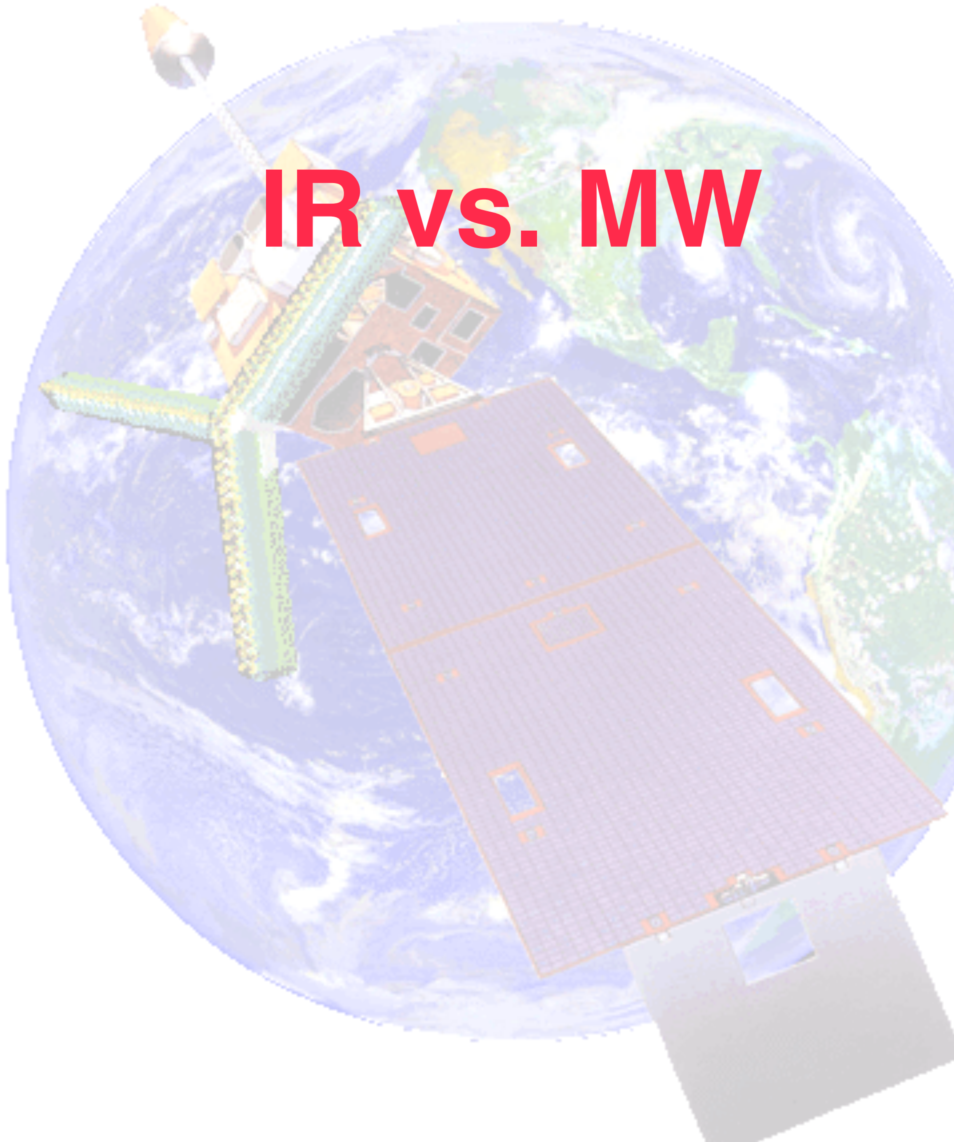


- **Radiometric sensitivity**
  - Must be no worse than AMSU (≤ 1 K)
- **Spatial resolution**
  - At nadir: ≤ 50 km for T; ≤ 25 km for q
- **Spectral coverage**
  - Tropospheric T-sounding: Must use 50-56 GHz
    - Note: Higher frequencies (118 GHz, etc.) cannot penetrate to the surface everywhere (e.g., tropics)
    - Bottom 2 km (PBL) is the most important/difficult part and must be adequately covered
  - Tropospheric q-sounding: Must use 183 GHz (AMSU-B channels)
    - Note: Higher frequencies (325 or 450 GHz) cannot penetrate even moderate atmospheres
  - Convective rain: 183 GHz (AMSU-B channels) method proven
  - "Warm rain": 89 + 150 GHz (Grody) - *use 50 GHz instead of 89*
- **Temporal coverage from GEO**
  - T-sounding: Every 30 minutes @ 50 km resolution *or better*
  - Q-sounding: Every 30 minutes @ 25 km resolution *or better*

These are strawman performance goals for GeoSTAR #1 (to be improved by x2 next)

Applications

- **Weather forecasting** **-Improve regional forecasts; severe storms**
  - All-weather soundings - standalone, but also complements IR soundings
  - Full hemispheric soundings @<50/25 km every ~ 30 minutes (continuous)
  - “Synoptic” rapid-update soundings => Forecast error detection; 4DVAR applications
- **Hurricane diagnostics** **-Quintessential hurricane sensor**
  - Scattering signal from hurricanes/convection easily measurable
  - Measure location, intensity & vertical structure of convective bursts
  - Detect intensification/weakening in NRT, frequently sampled (~ 10 minutes)
  - Measure all three phases of water: vapor, liquid, ice - *vertically resolved!*
- **Rain** **-Complement GPM**
  - Full hemisphere @ ≤ 25 km every 30 minutes (continuous) - both can be improved
  - Complements GPM/TRMM: fill space-time gaps through “data fusion” methods
  - Measure snowfall, light rain, intense convective precipitation (per Weng and per Staelin)
- **Tropospheric wind profiling** **-NWP, transport applications**
  - Surface to 300 mb; adjustable pressure levels; very high temp.res.; *in & below clouds*
- **Climate research** **-Hydrology cycle, climate variability**
  - Stable & continuous MW observations => Long term trends in T & q and storm stats
  - Fully resolved diurnal cycle: water vapor, clouds, convection
  - “Science continuity”: GeoSTAR channels = AMSU channels



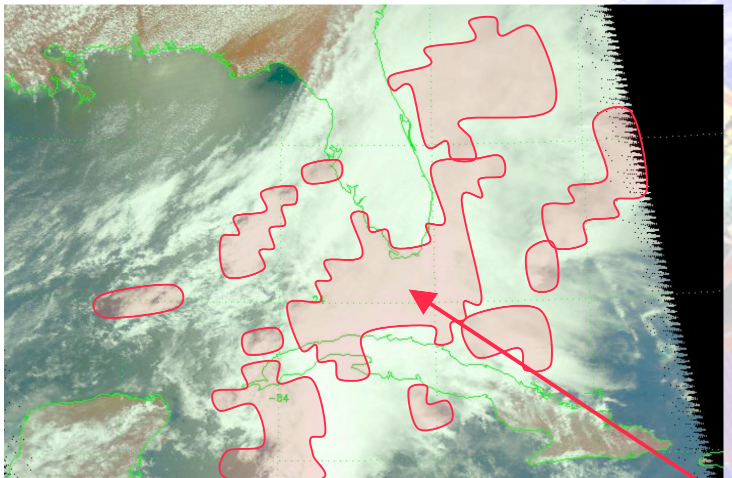
IR vs. MW

IR vs. MW: Pros & Cons

- **Spatial resolution**
  - IR vs. MW: 10-15 km vs. 15-50 km hor.res.; 1-1.5 km vs. 2-3 km vert.res.
- **Basic sounding accuracy**
  - IR vs. MW: 1 K vs. 1.5 K for T(z); 15% vs. 20% for q(z); none vs. 40% for L(z)
- **Scene coverage**
  - Cloud free: IR outperforms MW (but IR = MW in coverage)
  - Partly cloudy: IR < MW (IR depends on "cloud clearing", a noise-amplifying process)
  - Fully cloudy, storms: MW far outperforms IR ("cloud clearing" cannot be done)
- **Hurricanes & severe storms**
  - IR can only see cloud tops, often obscured by cirrus shields
  - MW can see to surface (except in heavy precipitation: switch to convection observations)
- **Summary**
  - IR is best suitable for global observations and storm precursor conditions in clear sky
  - MW is best suited for observing in/through storms and precursor conditions in clouds

IR vs. MW: Coverage - 1

May 16, 2006: Stormy case

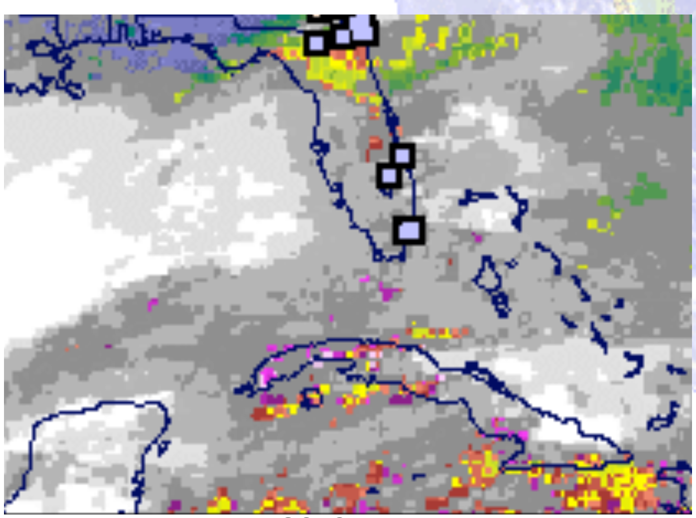


AIRS Vis/NIR

White: Poor retrievals (“qual” = 2)

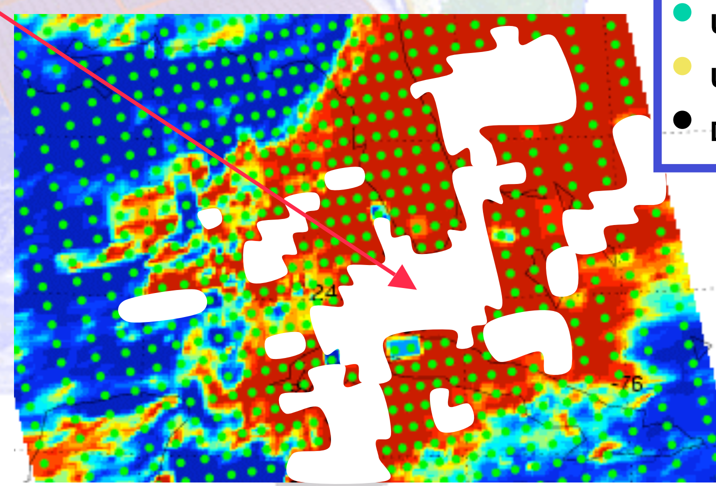
AIRS cloud-cleared retrievals

AIRS IR+MW



GOES soundings

AIRS quality flags
- Use with confidence
- Use with caution
- Do not use

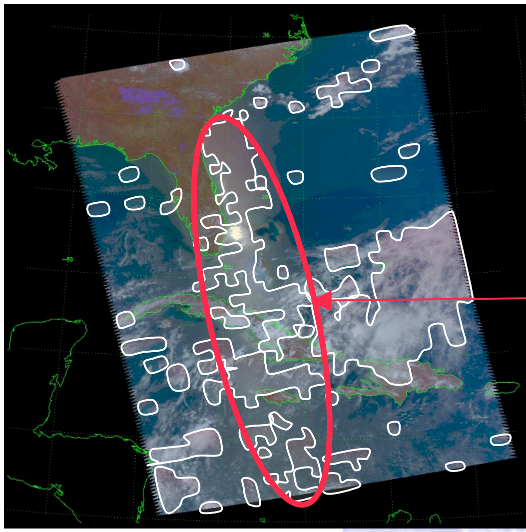


AIRS MW-only retrievals

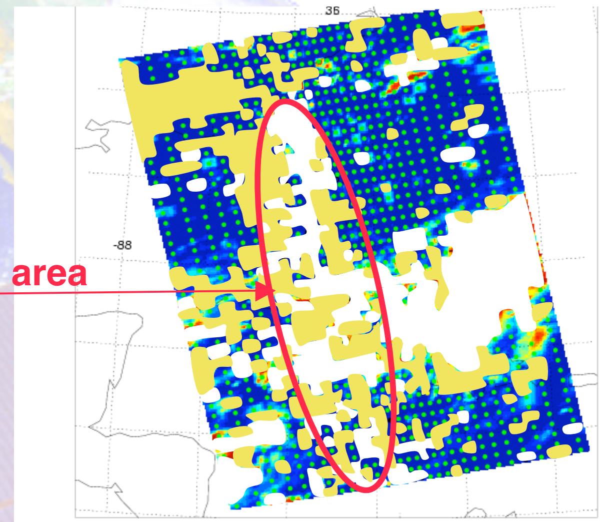
AIRS MW

IR vs. MW: Coverage - 2

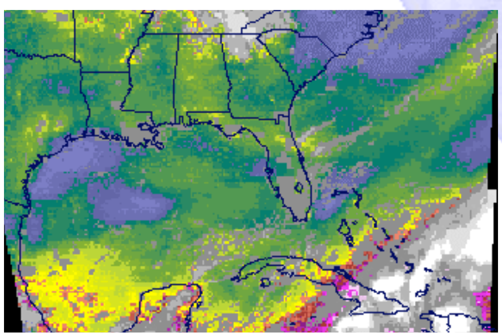
May 20, 2006: Good-weather case

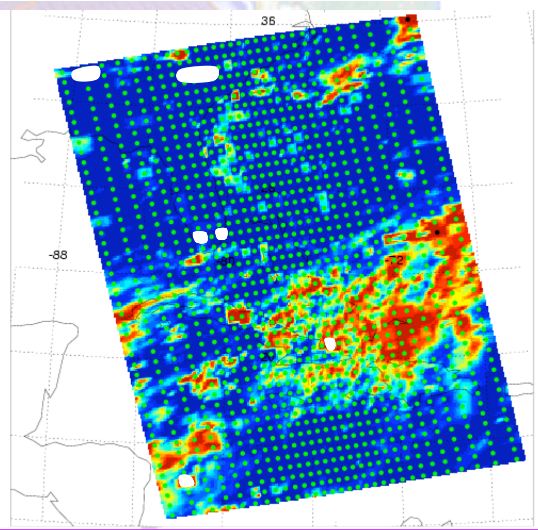


Note sun glint area



AIRS
IR+MW



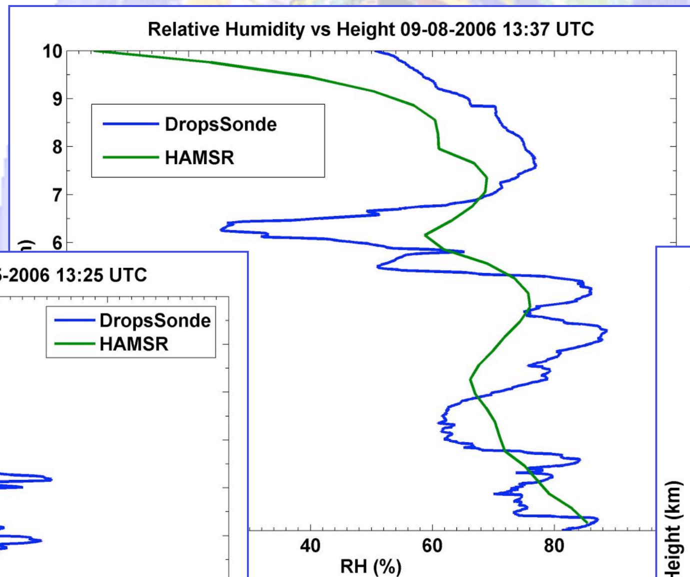


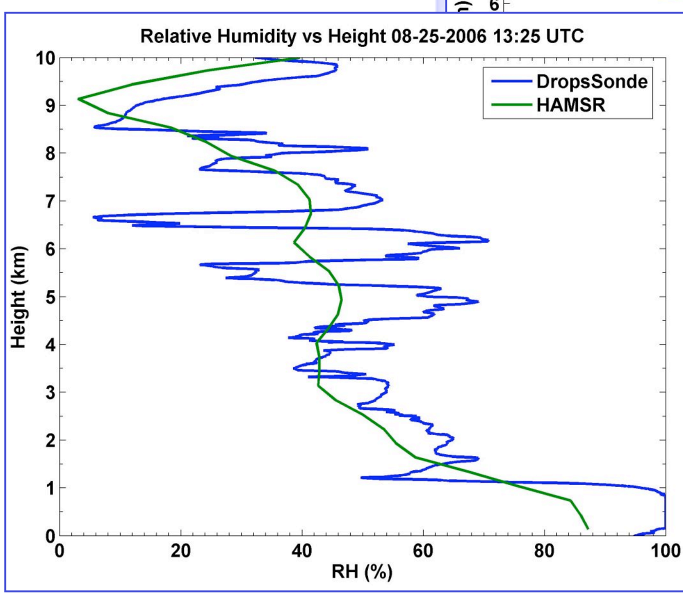
AIRS
MW

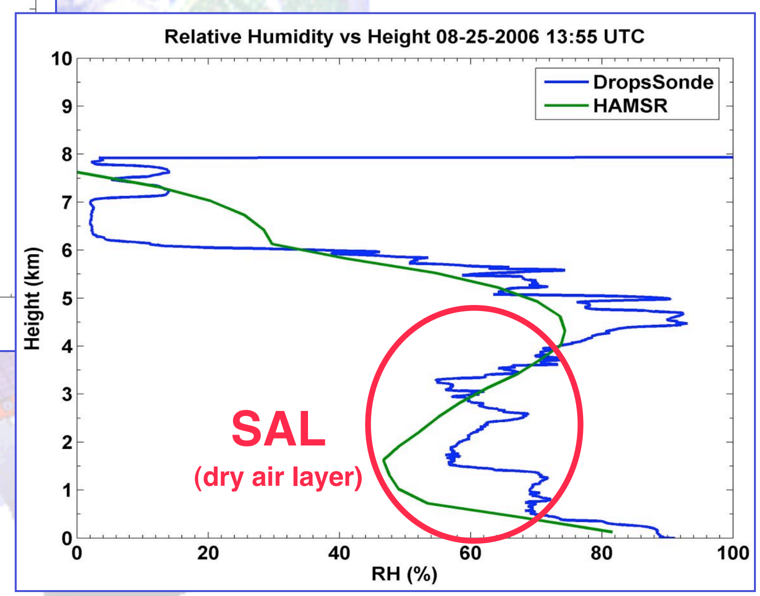
Example MW Soundings

Aircraft sounder HAMSR (ATMS prototype)
Results from recent NAMMA hurricane field campaign/Cape Verde

Water vapor retrievals







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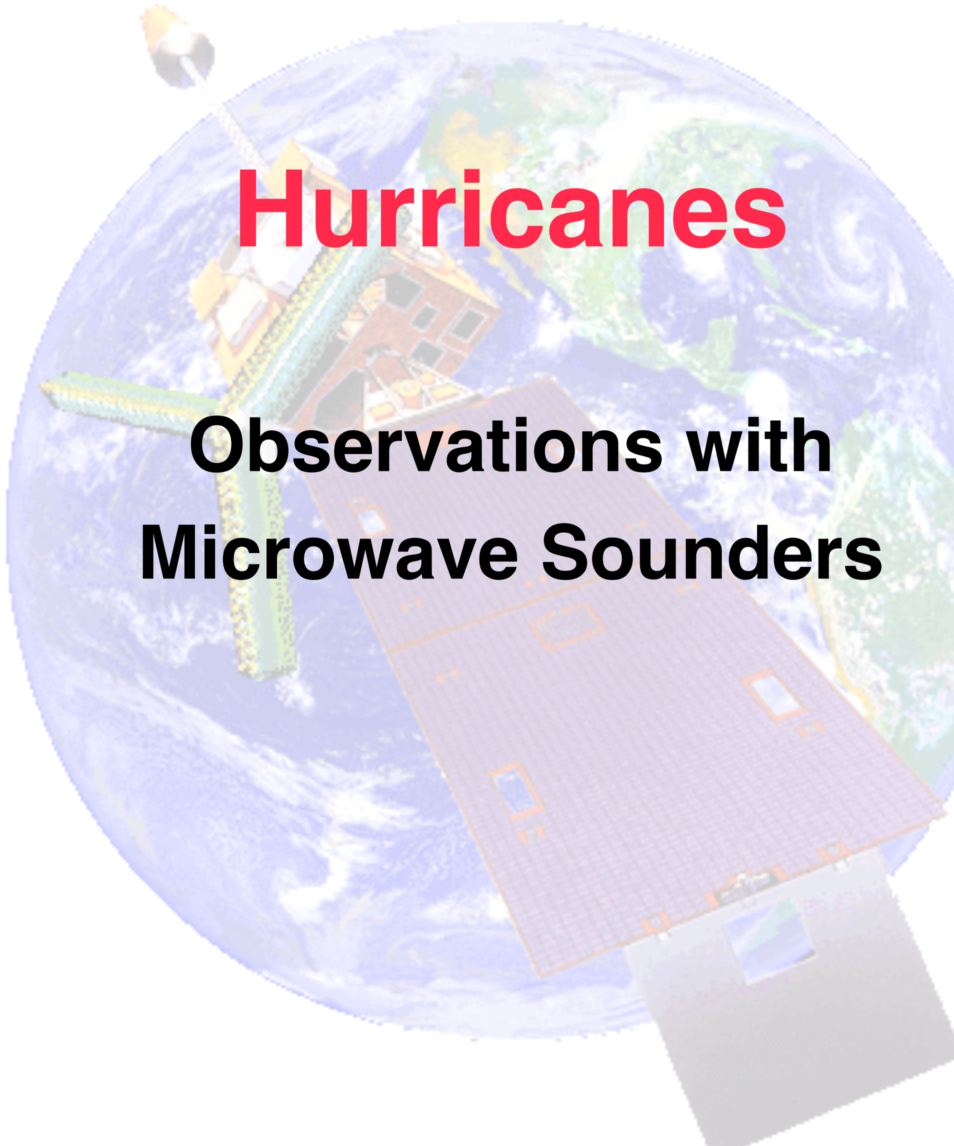


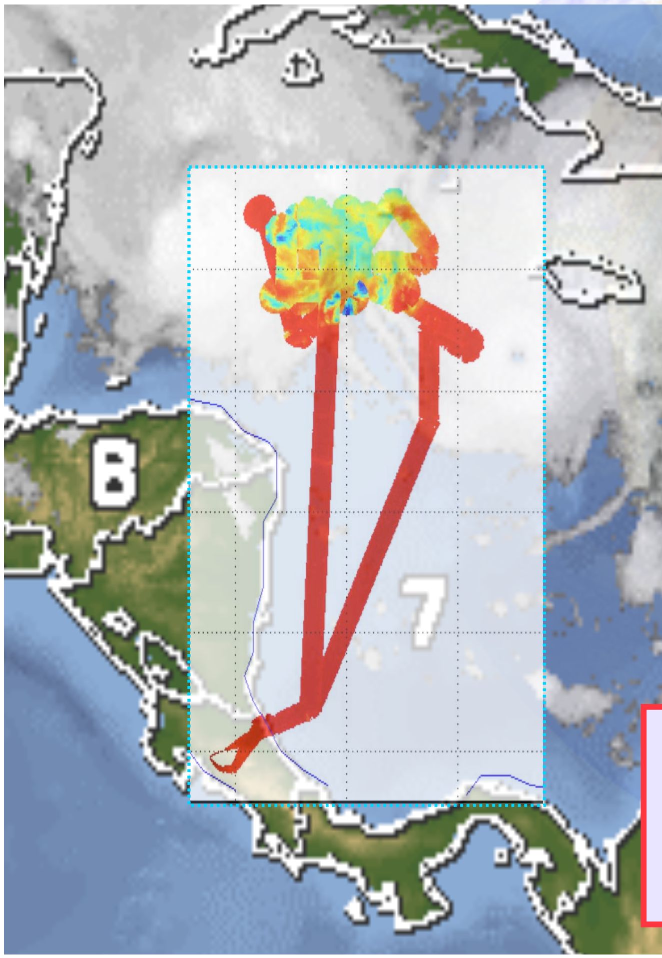
Hurricanes

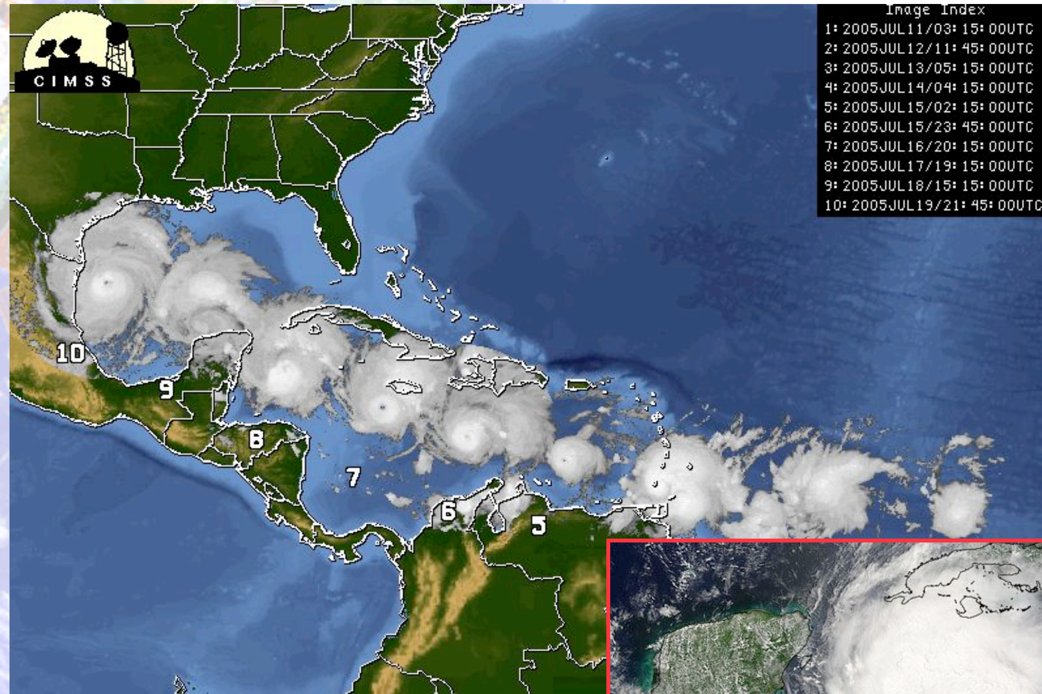
Observations with Microwave Sounders

TCSP Example: Hurricane Emily

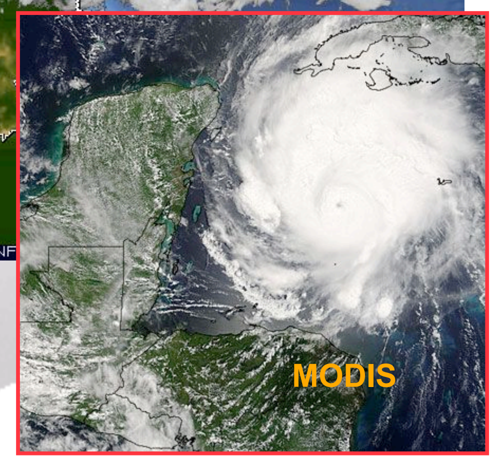
TCSP: NASA hurricane field campaign, Costa Rica, July 2005

HAMSR (ATMS prototype built at JPL) flying on ER-2



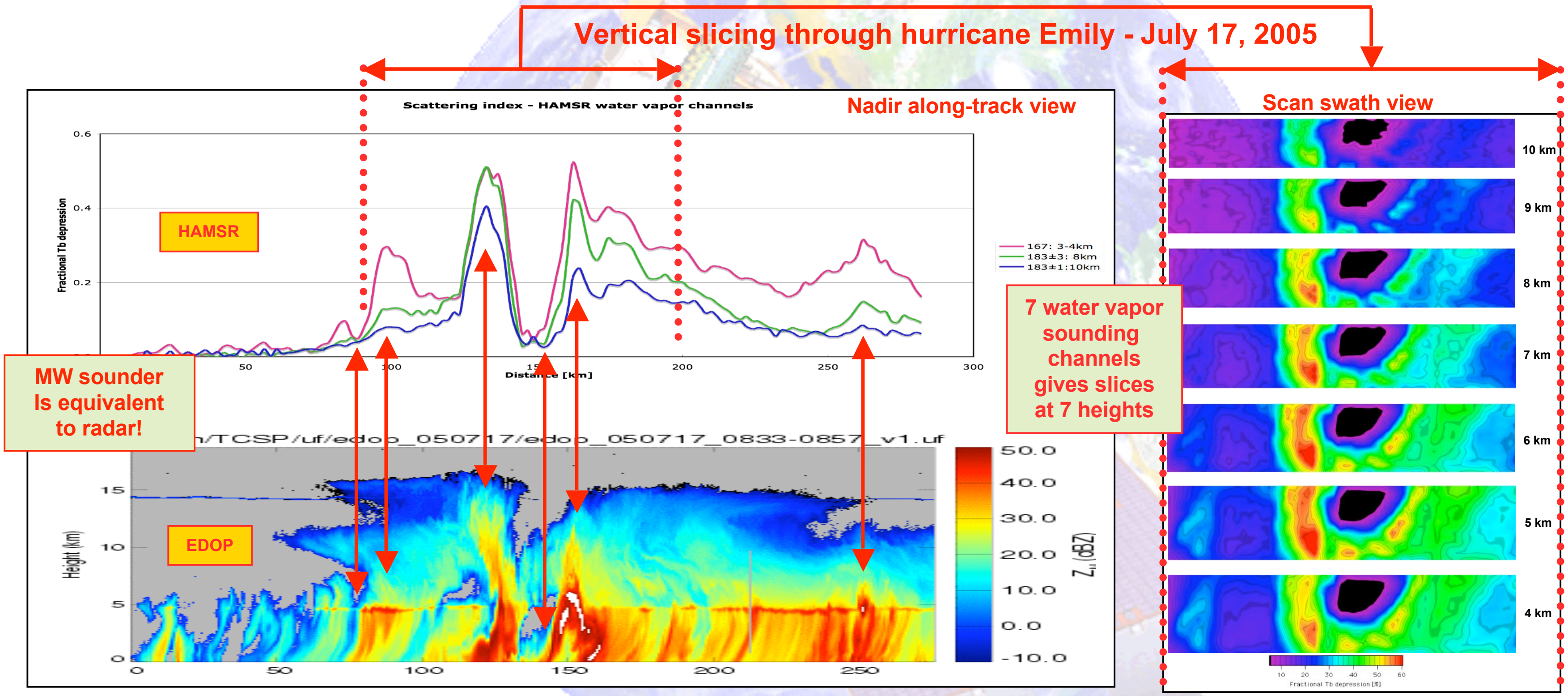


- **July 17, 2005**
- **Overflights at 0730-1200 UT**
- **Strength @ 0900: 938 mb/130 kt, declining (strong Cat. 4)**



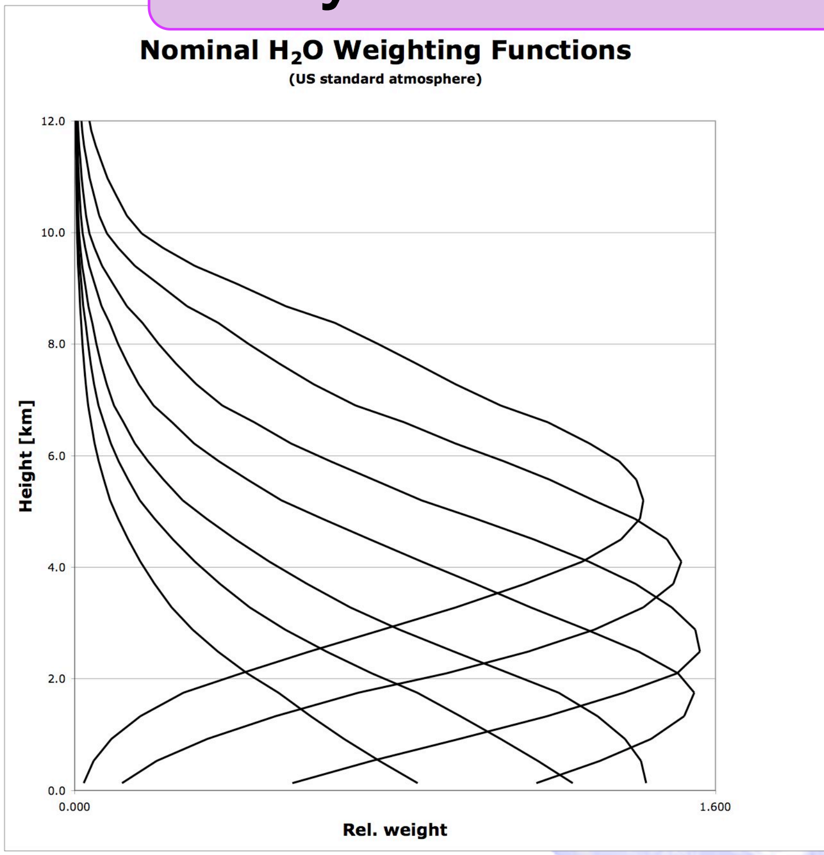
MW = “Poor man’s radar”

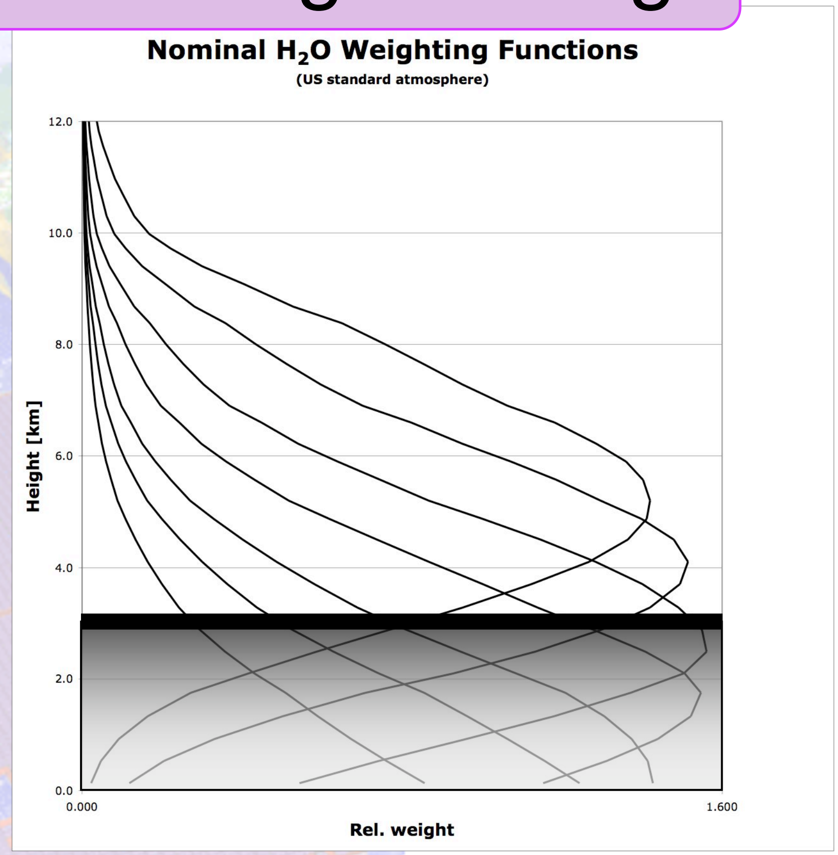
Hurricane observations with MW sounder (HAMSR) compared with doppler radar (EDOP)



<u>Potential applications:</u>
“Radar reflectivity”; Convective rain; Ice water path; Convective intensity
Height resolved!
(Algorithm dev. under way)

Physical Basis for Scattering Profiling





RTE: $Tb = \varepsilon \bullet T_{sfc} \bullet \tau + \int T_{atm} d\tau$

Opaque channels ($\tau \approx 0$):

- $Tb \approx T_{atm}$ @ w.func peak

Transparent channels ($\tau \approx 1$) :

- $Tb \in [T_{atm}, \varepsilon \bullet T_{sfc}]$
- If ε is low, $Tb << T_{phys}$

Scattering layer acts like low-ε "surface"

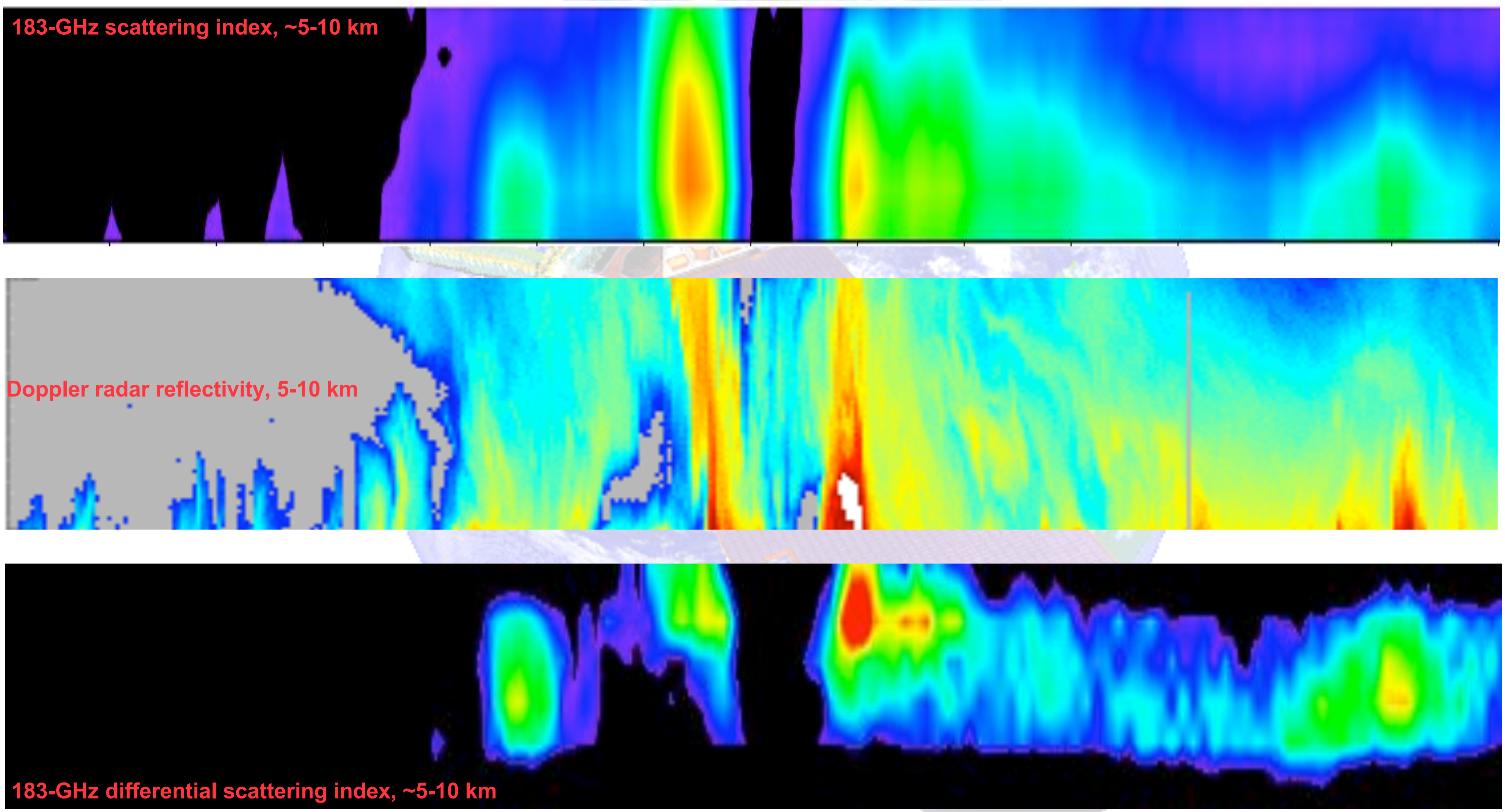
- Cold "Tb_{sfc}" replaces lower range of integral
- Result is $Tb_{scatt} < Tb_{normal}$

ΔTb vs. channel => vertical distribution of scattering

ΔTb vs. band (wavelengths) => particle size info

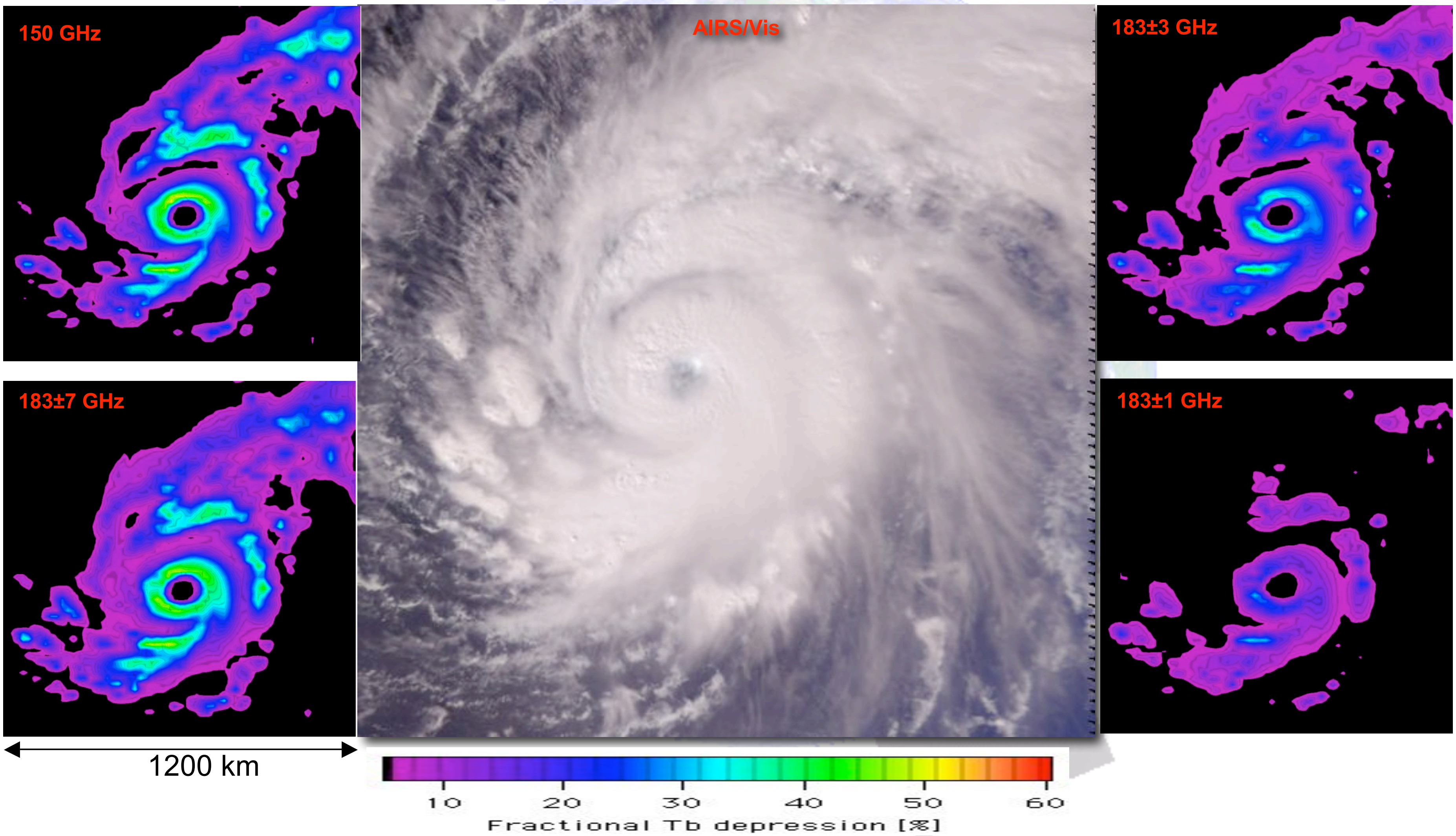
- for d < 1 mm (otherwise in Mie regime)

Vertical Distribution of Scattering - Emily

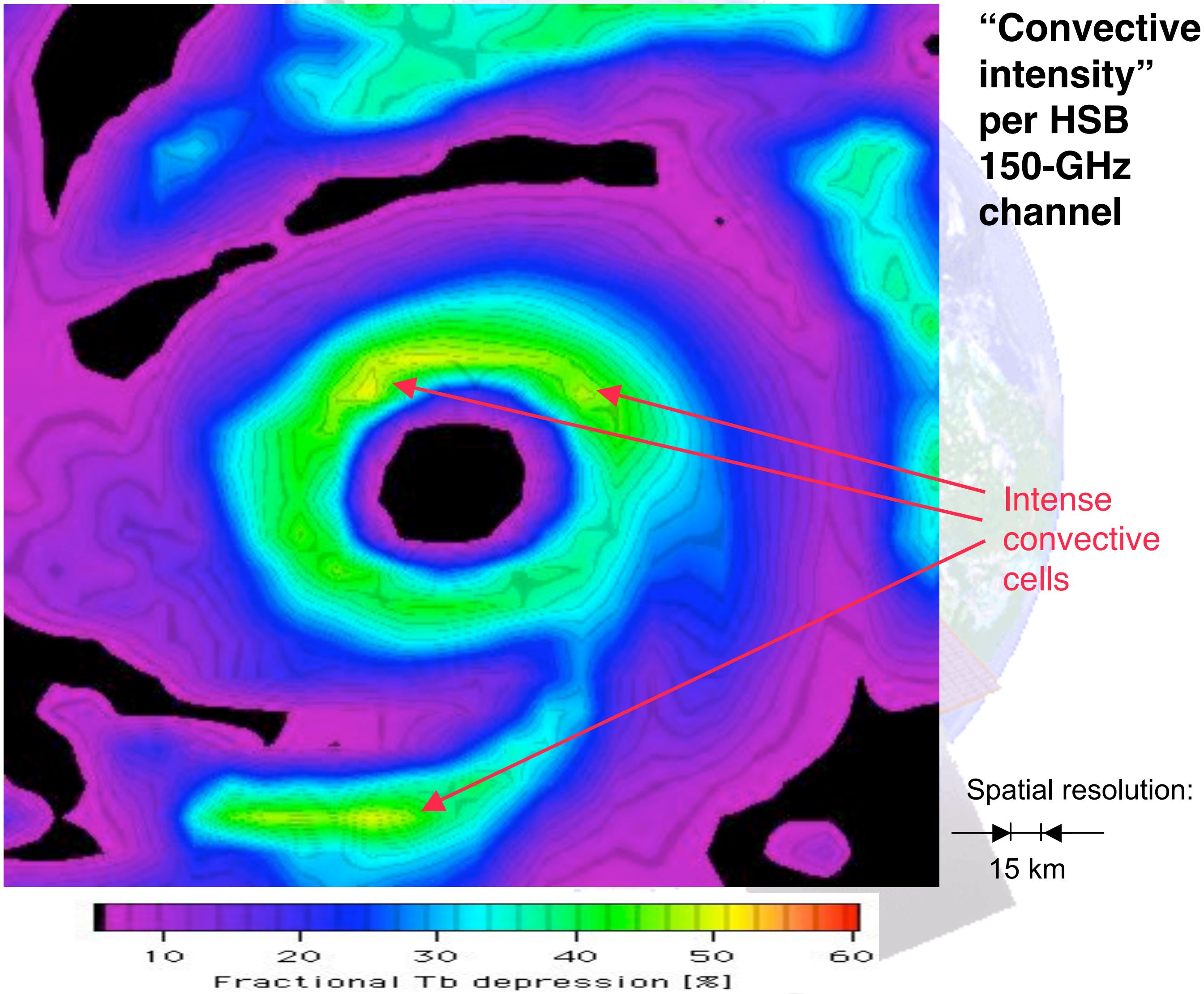


The View From Space

Aqua/HSB —December 8, 2002, 03:50 UTC — Supertyphoon Pongsona over Guam



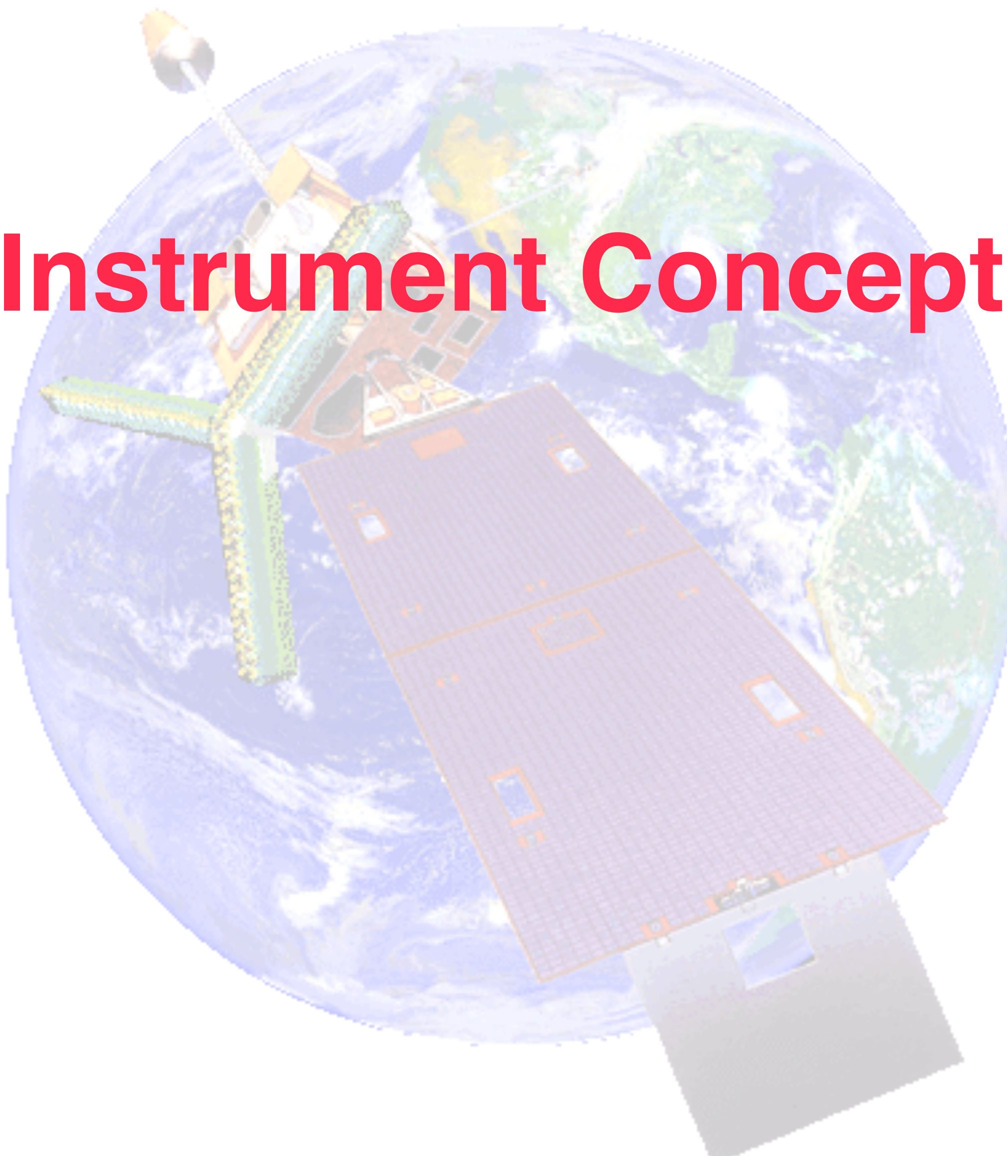
Closeup of Pongsona



"Convective intensity" per HSB 150-GHz channel

Spatial resolution:

15 km

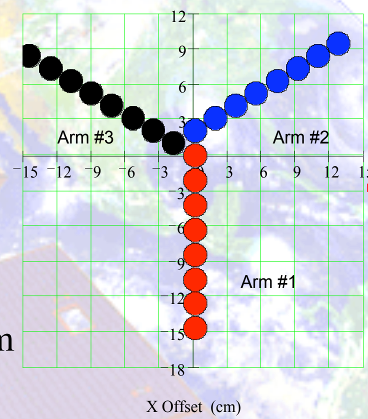


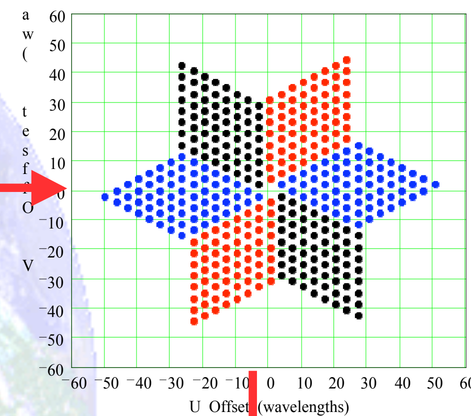
Instrument Concept

GeoSTAR System Concept

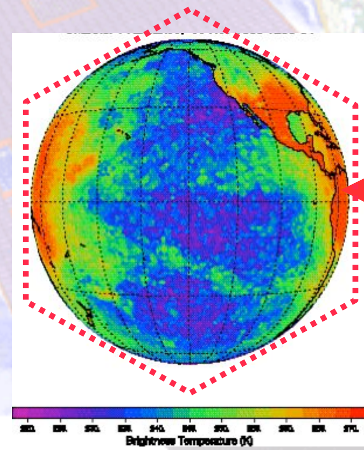
- **Concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One "Y" per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth

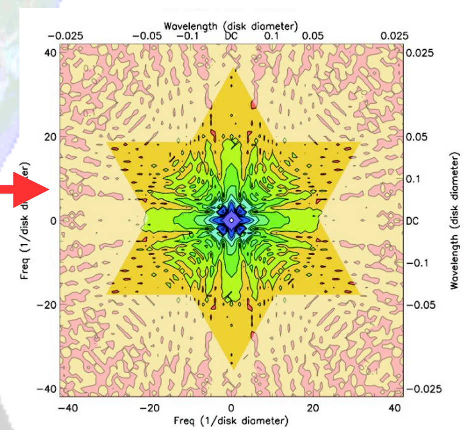
Receiver array & resulting uv samples





Example: AMSU-A ch. 1





What GeoSTAR Measures

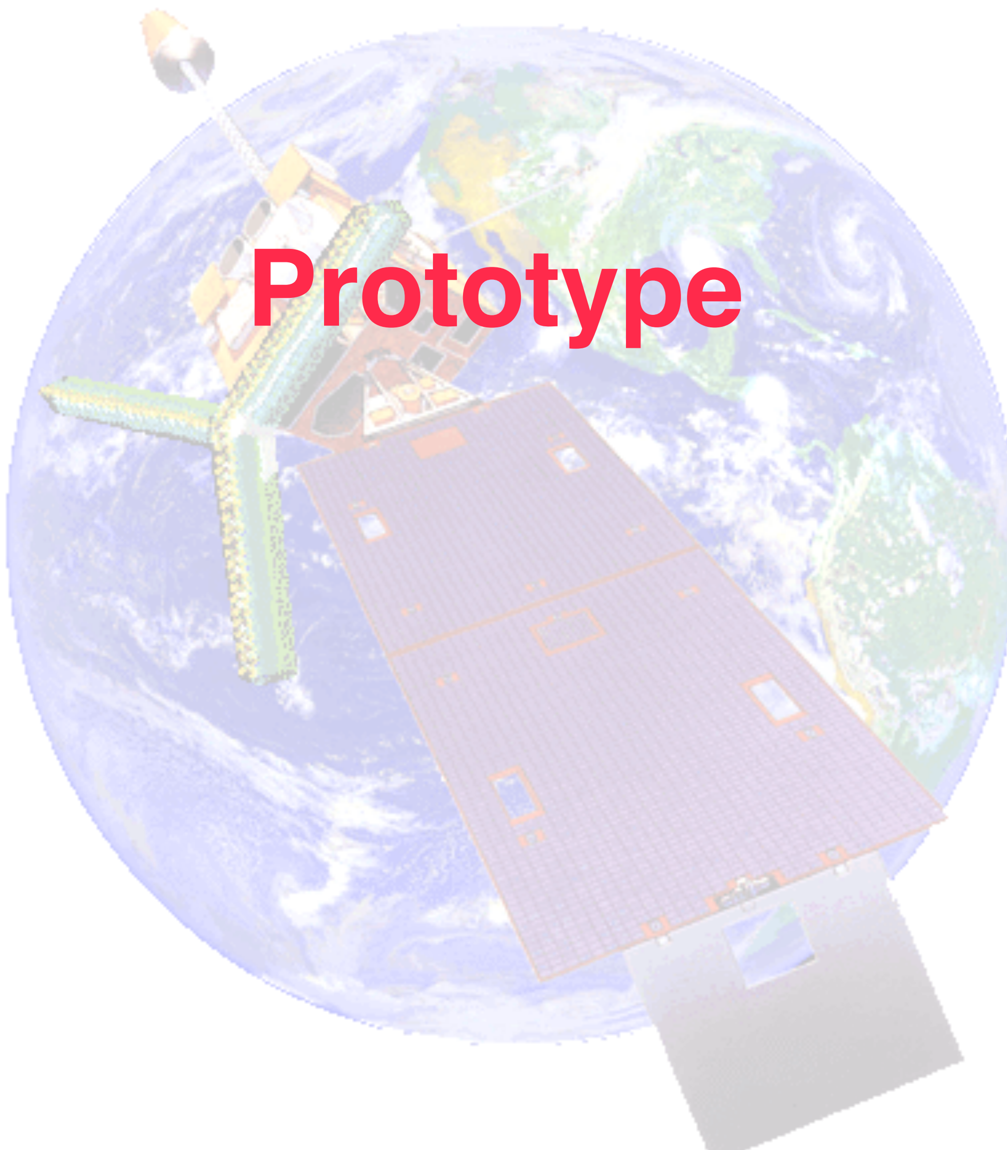
- **Visibility measurements**
  - Essentially the same as the spatial Fourier transform of the radiometric field
  - Measured at fixed uv-plane sampling points - One point for each pair of receivers
  - Both components (Re, Im) of complex visibilities measured
  - Visibility = Cross-correlation = Digital 1-bit multiplications @ 100 MHz
  - Visibilities are accumulated over calibration cycles —> Low data rate
- **Calibration measurements**
  - Multiple sources and combinations
  - Measured several times a second = calibration cycle
- **Interferometric imaging**
  - All visibilities are measured simultaneously - On-board massively parallel process
  - Accumulated on ground over several minutes, to achieve desired NEDT
  - 2-D Fourier transform of 2-D radiometric image is formed - *without scanning*
- **Spectral coverage**
  - Spectral channels are measured one at a time - LO tunes system to each channel

Calibration

- **GeoSTAR is an *interferometric* system**
  - Therefore, *phase calibration* is most important
  - System is designed to maintain phase stability for tens of seconds to minutes
  - Phase properties are monitored beyond stability period (e.g., every 20 seconds)
- **Multiple calibration methods**
  - Common noise signal distributed to multiple receivers —> complete correlation
  - Random noise source in each receiver —> complete de-correlation
  - Environmental noise sources monitored (e.g., sun's transit, Earth's limb)
  - Occasional ground-beacon noise signal transmitted from fixed location
  - Other methods, as used in radio astronomy
- **Absolute radiometric calibration**
  - One conventional Dicke switched receiver measures "zero baseline visibility"
    - Same as Earth disk mean brightness temperature (= Fourier offset, the "a_0 term" in a F-series)
  - Also: compare with equivalent AMSU observations during over/under-pass
  - The Earth mean brightness is highly stable, changing extremely slowly

GeoSTAR Data Processing

- **On-board measurements**
  - Instantaneous visibilities: high-speed cross-correlations
  - Accumulated visibilities: accumulated over calibration cycles
  - Calibration measurements
- **On-ground image calibration**
  - Apply phase calibration: Align calibration-cycle visibility subtotals
  - Accumulate aligned visibilities over longer period —> Calibrated visibility image
- **On-ground image reconstruction**
  - Inverse Fourier transform of visibility image, for each channel
  - Complexities due to non-perfect transfer functions are taken into account
- **On-ground geophysical retrievals**
  - Conventional approach
  - Applied at each radiometric-image grid point


Prototype

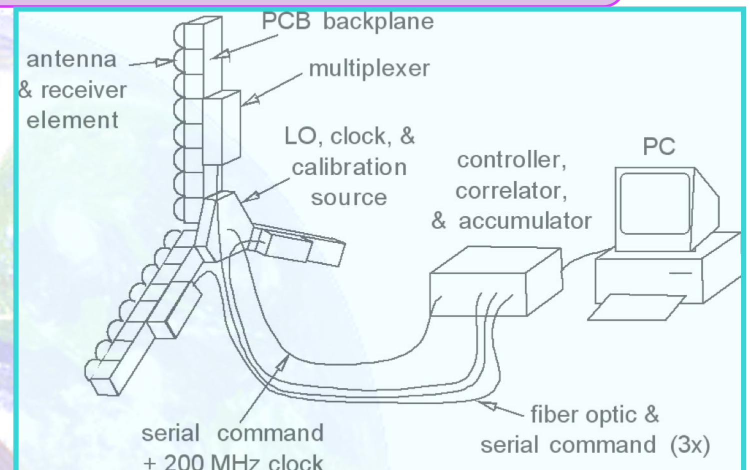
GeoSTAR Prototype Development

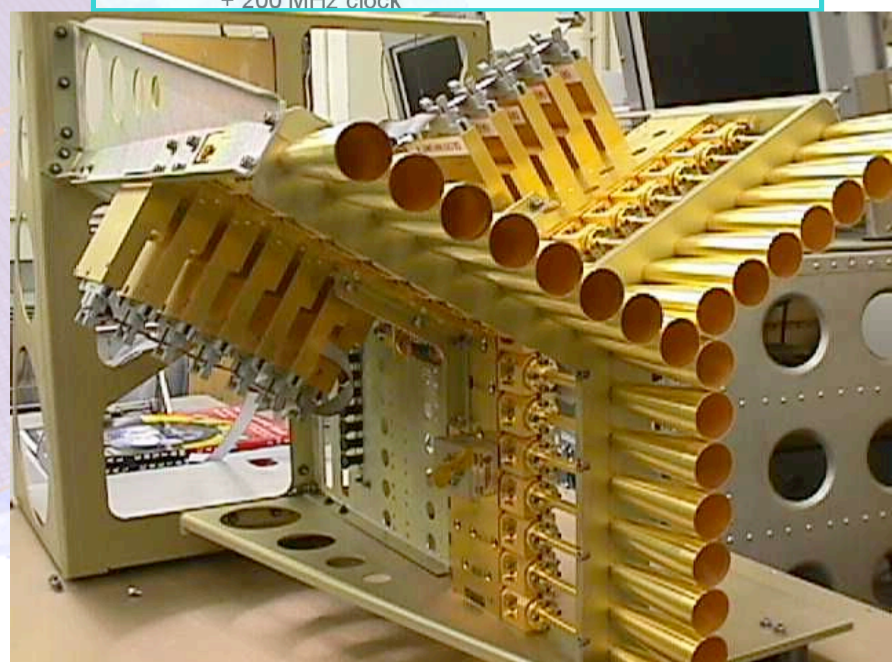
- **Objectives**
  - Technology risk reduction
  - Develop system to maturity and test performance
  - Evaluate calibration approach
  - Assess measurement accuracy
- **Small, ground-based**
  - 24 receiving elements - 8 (9) per Y-arm
  - Operating at 50-55 GHz
  - 4 tropospheric AMSU-A channels: 50.3 - 52.8 - 53.71/53.84 - 54.4 GHz
  - Implemented with miniature MMIC receivers
  - Element spacing as for GEO application (3.5 λ)
  - FPGA-based correlator
  - All calibration subsystems implemented

Now undergoing testing at JPL

Performance is excellent

Breakthrough development!





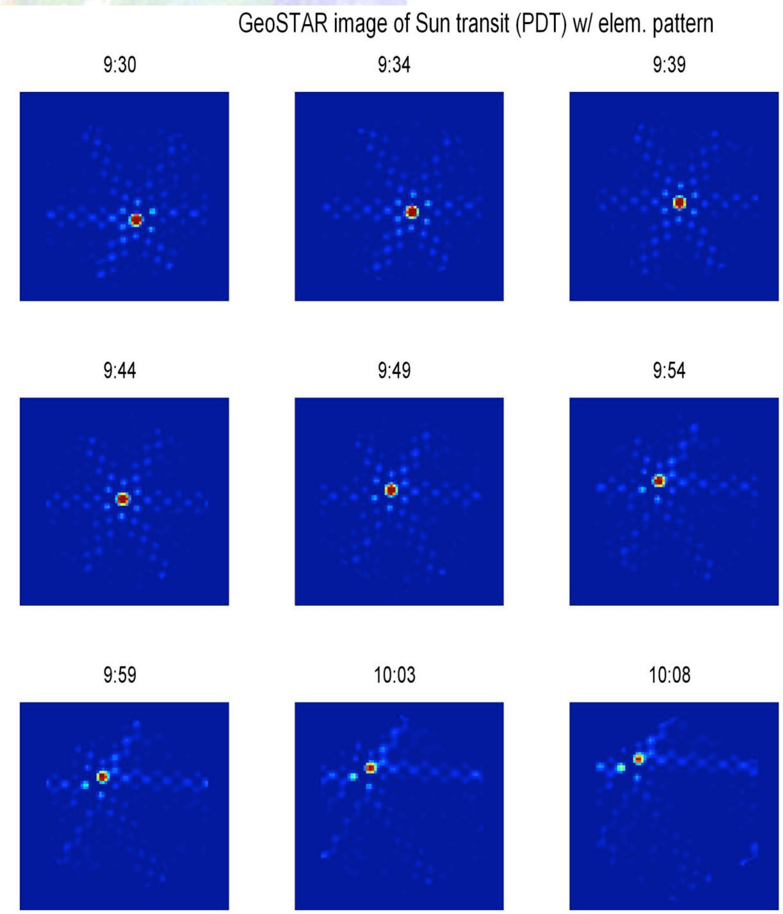
GeoSTAR First Light: Solar Transit at JPL

March 2005

GeoSTAR taken outside to observe the sun

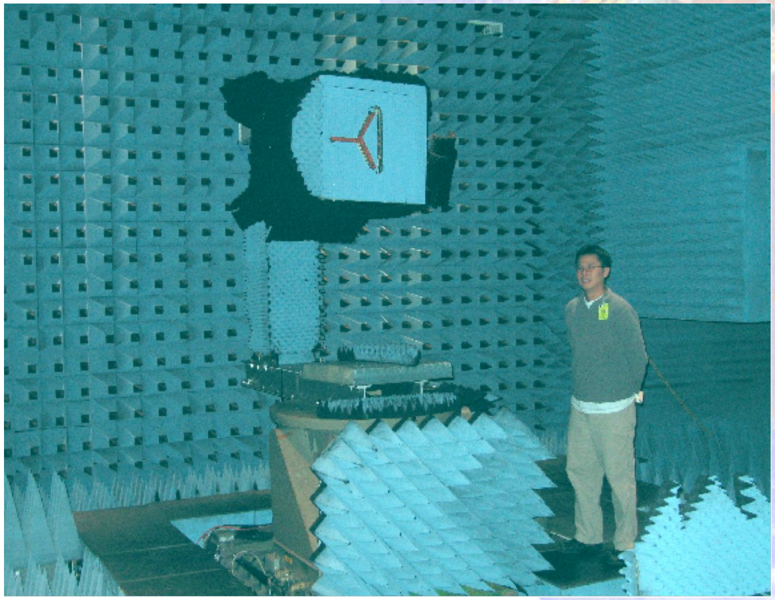
Pointed upwards at 45° elevation angle

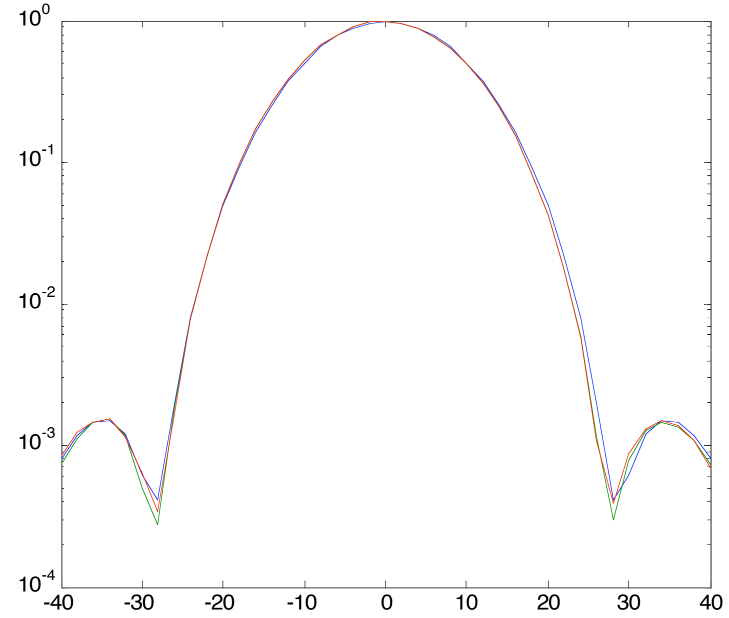
About 80 minutes of data during transit through ~20° FOR



Antenna Tests at NASA GSFC

September 2005





Excellent antenna patterns

First Images of Real Scenes

November 2005

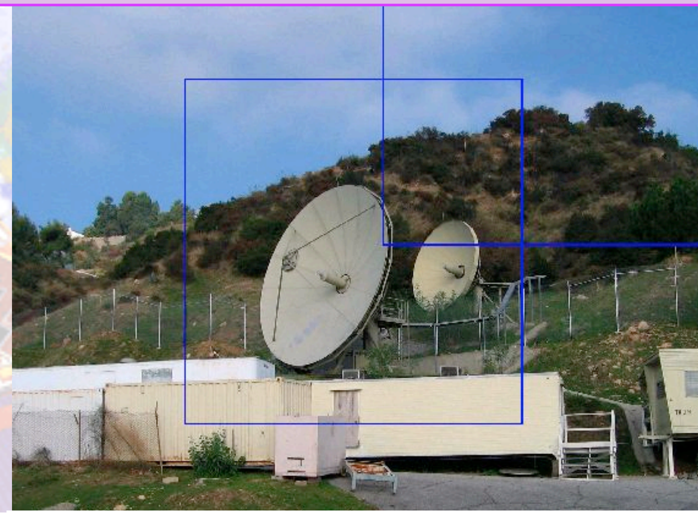
-Images reconstructed from 5-minute interferometric measurement sequences

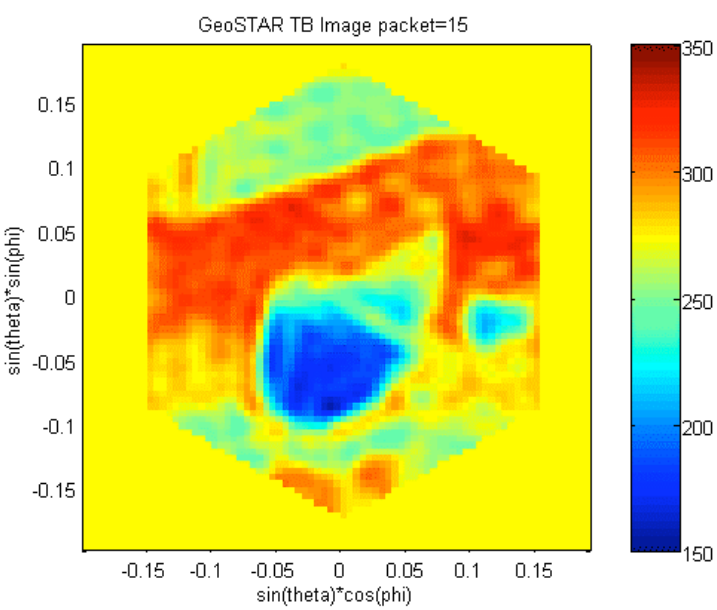
-Hexagonal central imaging area shown

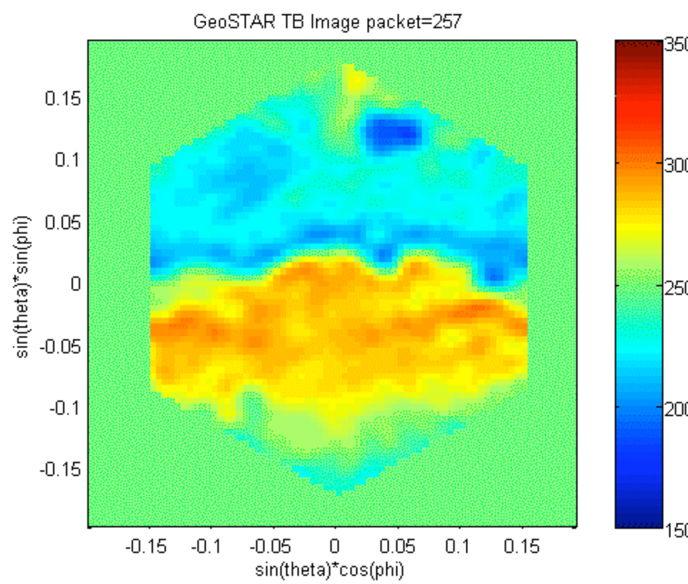
-Aliasing from outside central imaging area can be seen

These effects are well understood and can be compensated for, but they will not appear in GEO (background Is 2.7 K)

This was a first - a major achievement!

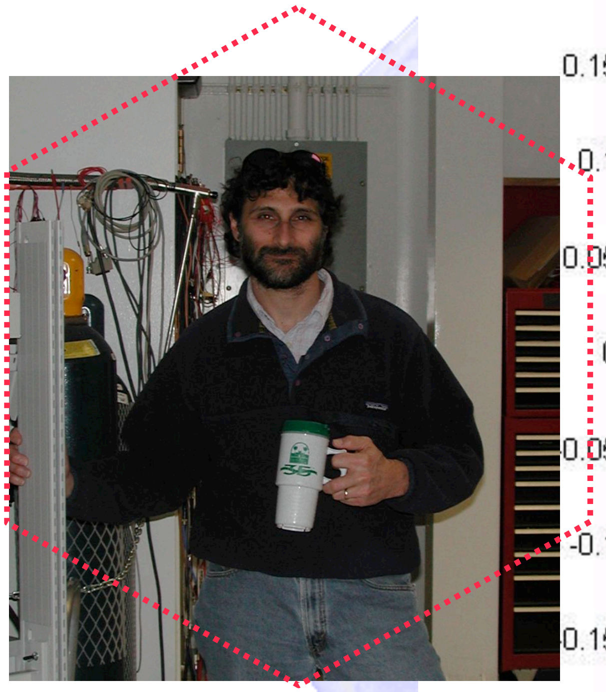


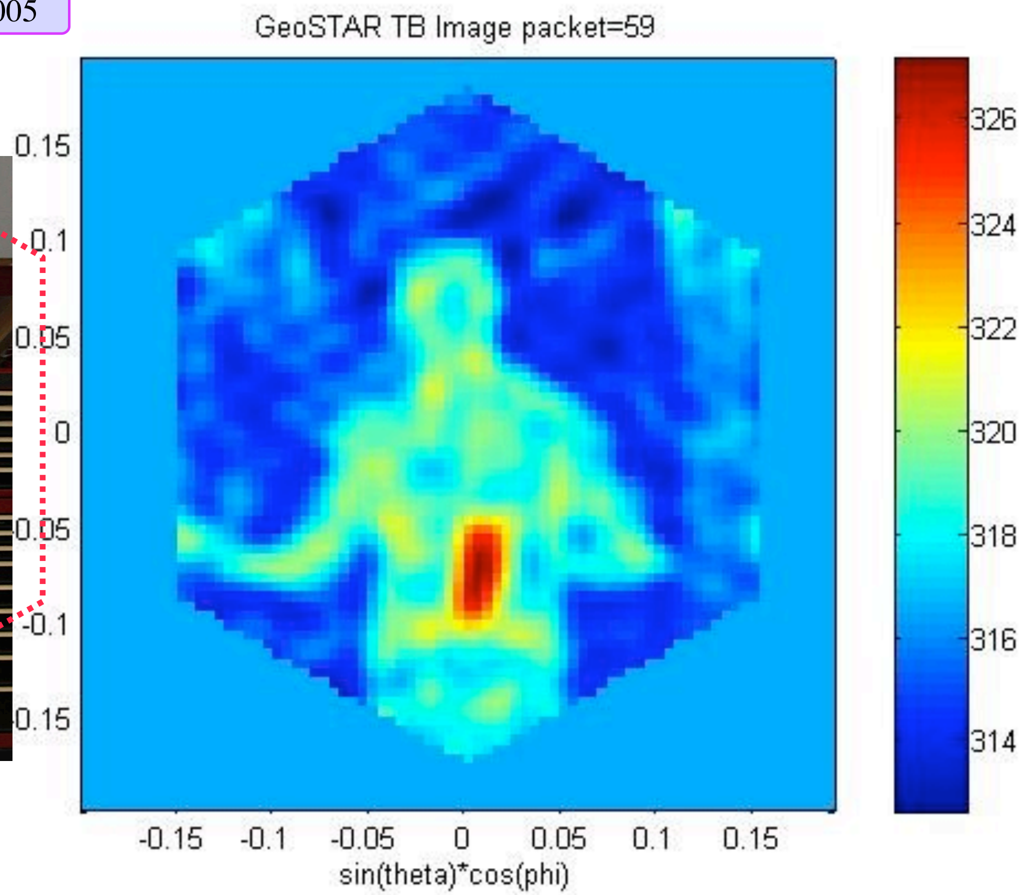




Indoor Target!

November 2005





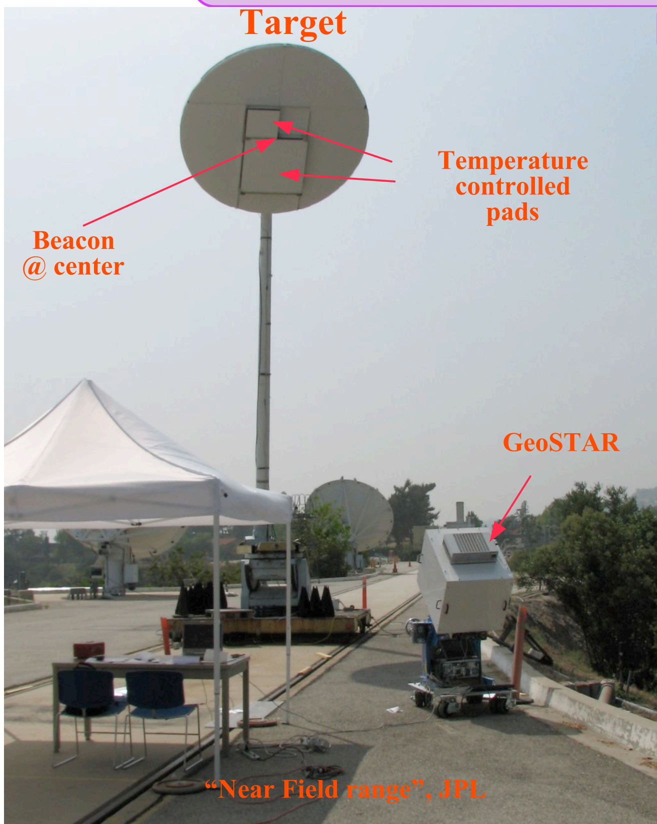
-We have developed a method to compensate for distortions when target is in near field

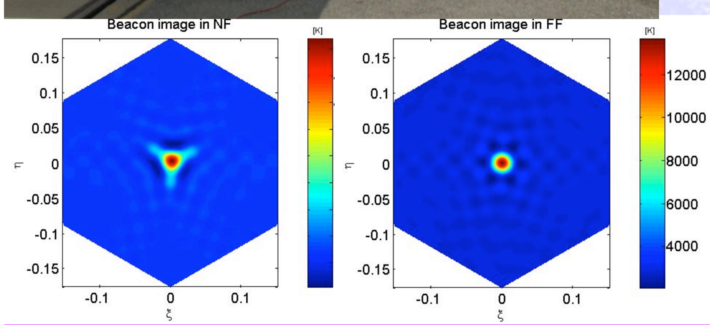
-This allows us to use near-field targets to measure the performance of the system

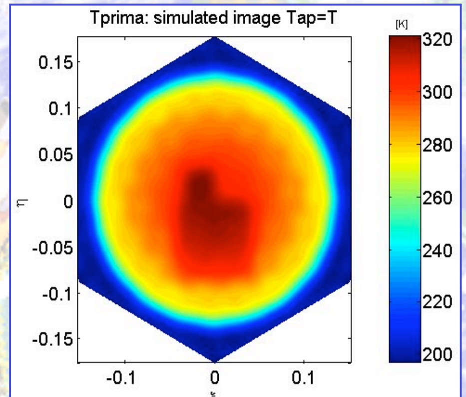
-An effort is now under way to measure mocked-up “Earth from GEO” calibration targets

Quantitative Calibration

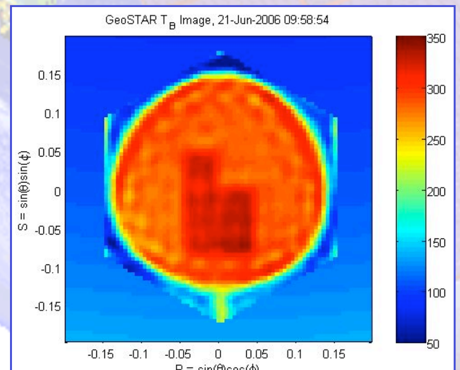
June 2006





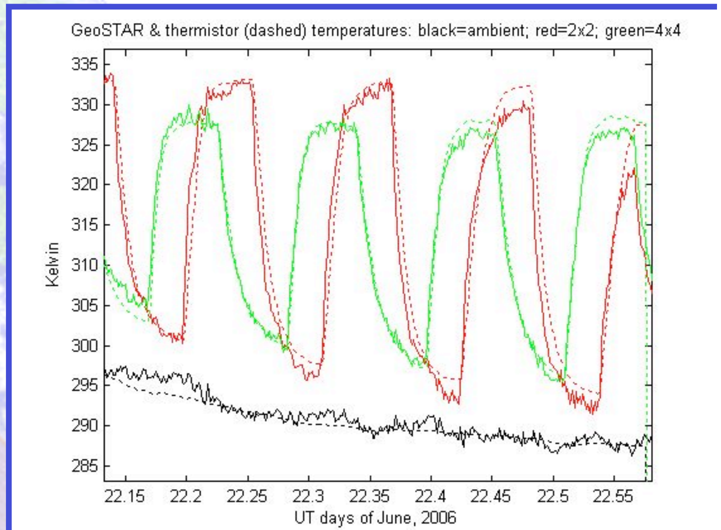


Raw synthesized image



Processed image†

† De-aliased, ant.patt. Corr; Not sidelobe-corrected



Retrieved vs. measured temperatures

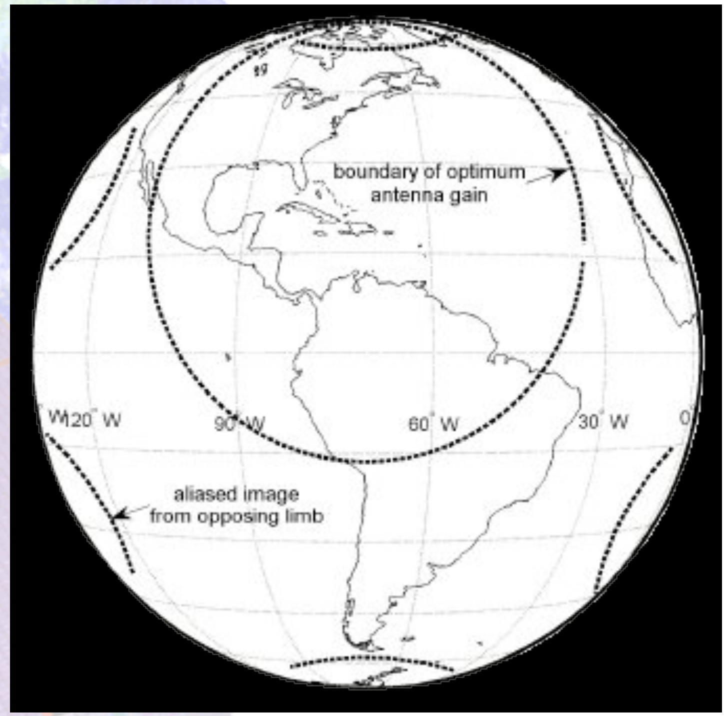
Red: Large pad (4'x4' controlled)
Green: Small pad (2'x2' controlled)
Black: Main target (ambient)

Solid: GeoSTAR retrieval
Dotted: Thermistor average

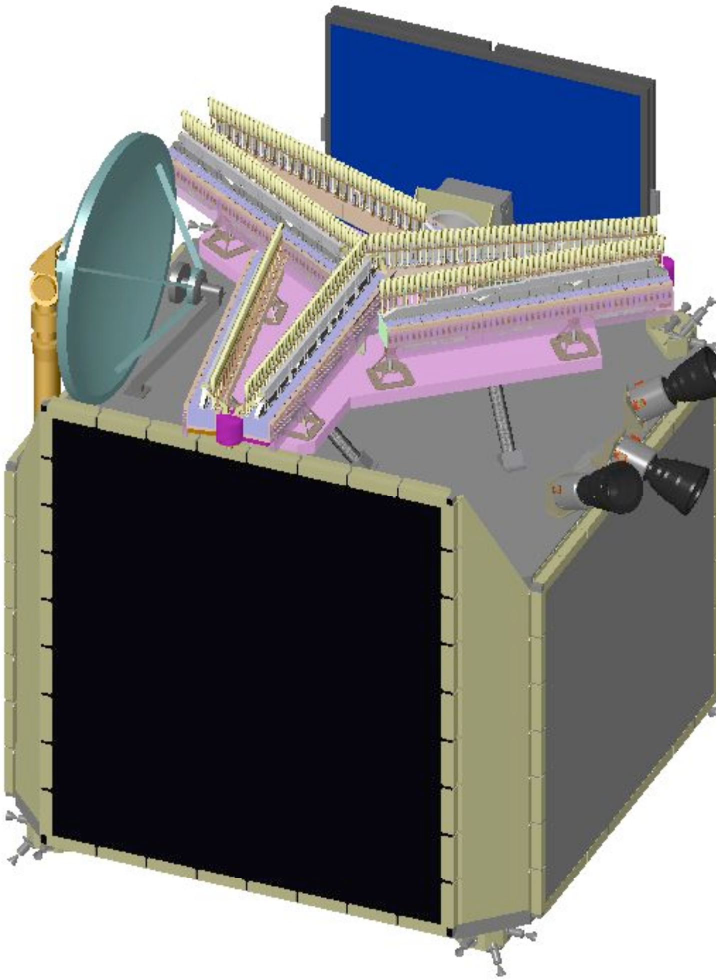
Mission Development

Notional Mission

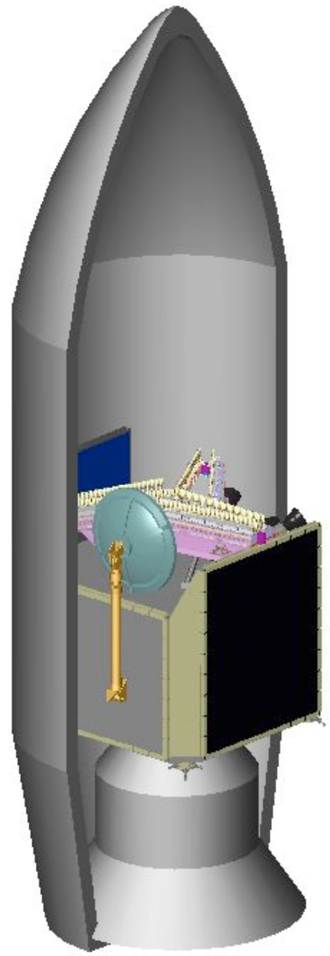
- **Objective: Observe US hurricanes & severe storms**
  - Primary: Atlantic hurricanes
  - Secondary: CONUS severe storms; E. Pac. hurricanes
- **ROI focused near E. Carribbean**
  - Center @ 75°W, 20°N (permanently pitch GeoSTAR)
    - Can be pointed in other directions
  - 90+ % of visible disc is in alias-free region
    - Can be narrowed down (lower cost => risk mitigation)
  - Highest sensitivity in "circle" of radius 45°
    - Exploring antenna designs to maximize high-sensitivity region
- **Adequate sensitivity**
  - ~ 20 minutes "integration time" to reach 1 K for water vapor (183 GHz) in central part of ROI
    - T-band (50 GHz) is twice as sensitive/responsive
    - Exploring designs to improve these numbers
    - Exploring methods to increase temporal resolution



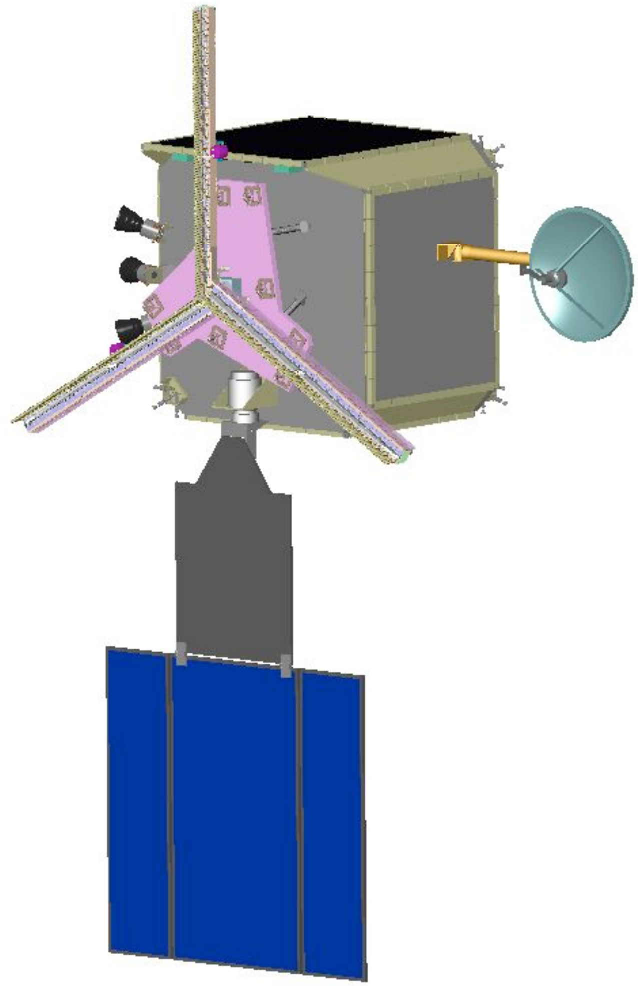
Platform Accommodation



Array arms folded for launch



Stowed in Delta fairing



Deployed on-orbit

Ball Aerospace

GEO Roadmap

- **Prototype: 2003-2006**
  - Fully functional system completed - now being tested & characterized
- **Ongoing risk reduction: 2005-2008**
  - Develop 183-GHz compact/lightweight multiple-receiver modules
  - Develop efficient radiometer assembly & testing approach
    - Reduce cost per receiver
  - Migrate correlator design & low-power technology to rad-hard ASICs
- **Science and user assessment**
  - Forecast impact: OSSE under development
  - Algorithm development; applications
- **Space version (PFM): ~2007-2013**
  - Start formulation phase in 2007
  - Ready for launch in 2013 - Launch on GOES-R or PATH in 2014 or later
- **Demonstration mission: ~2014-2015 or later**
  - Joint NASA/NOAA mission
- **Transition to operational: after 1 year in research mode**
  - Part of operational GOES or PATH research mission

Conclusions

- **Prototype development has been a tremendous success**
  - Inherently very stable design; Excellent performance
  - Measurements confirm system models and theory
  - *Breakthrough development!*
- **Technology risk mostly retired**
  - Prototype demos key technologies
  - Remaining challenges are “engineering risks”
    - Further risk reduction will focus on efficient manufacture of large number of receivers
    - Design & fabrication of correlator ASIC is also an engineering issue, not technology
- **Science potential is tremendous**
  - GeoSTAR is ideally suited for GEO
    - “Synoptic” sensor - continuous 2D imaging/sounding snapshots of Earth disc
  - Soundings *in* hurricanes and severe storms
    - Water vapor, liquid water, ice water, precipitation - all vertically resolved
    - Can derive stability metrics (LI, CAPE, etc.), convective intensity
    - Now-casting: Detect sudden hurricane intensification/weakening
  - No other system can provide these capabilities with such spatial and temporal coverage/res.
- **Ready for space mission!**
  - GOES-R or “PATH” - Can be ready for launch ~2014

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

GEOSTAR A NEW SENSOR FOR GEO

COMING SOON:

SEE THIS IN MICROWAVE!

This work was carried out at the
Jet Propulsion Laboratory,
California Institute of Technology
under a contract with the
National Aeronautics and Space Administration.